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Search for dark matter produced in association with a Higgs boson decaying to a τ lepton pair in proton-proton collisions at $\sqrt{s} = 13$ TeV

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Abstract: A search for dark matter particles produced in association with a Higgs boson decaying into a pair of τ leptons is performed using data collected in proton-proton collisions at a center-of-mass energy of 13 TeV with the CMS detector. The analysis is based on a data set corresponding to an integrated luminosity of 101 fb^{-1} collected in 2017–2018. No significant excess over the expected standard model background is observed. This result is interpreted within the frameworks of the 2HDM+a and baryonic Z' benchmark simplified models. The 2HDM+a model is a type-II two-Higgs-doublet model featuring a heavy pseudoscalar with an additional light pseudoscalar. Upper limits at 95% confidence level are set on the product of the production cross section and the branching fraction for each of these two simplified models. Heavy pseudoscalar boson masses between 400 and 700 GeV are excluded for a light pseudoscalar mass of 100 GeV. For the baryonic Z' model, a statistical combination is made with an earlier search based on a data set of 36 fb^{-1} collected in 2016. In this model, Z' boson masses up to 1050 GeV are excluded for a dark matter particle mass of 1 GeV.

Keywords: Dark Matter, Hadron-Hadron Scattering, Higgs Physics, Tau Physics

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Contents

1 Introduction

Evidence for dark matter (DM) and its influence on the observed large-scale structure of the universe is well supported by numerous studies [1–4]. This evidence, along with the hypothesis that DM consists of long-lived weakly interacting massive particles, drives the search for potential DM production at the CERN LHC. Given the stringent constraints on weak interactions between DM and standard model (SM) particles, models incorporating beyond-the-SM (BSM) scalar sectors are of significant interest.

If DM is produced at the LHC, it is likely to escape direct detection because of its rare interaction with the matter that makes up the detectors. However, if DM candidates are produced alongside SM particles, such as the 125 GeV Higgs boson, they may create an imbalance in recorded momentum, resulting in a large amount of missing transverse momentum (p_T^{miss}). Such signatures are generically called "mono-Higgs". This paper reports on a search for the production of DM particles (χ) recoiling against a Higgs boson, which is reconstructed through its decay into a pair of τ leptons in both leptonic and hadronic decays. The data set used in this analysis was collected from proton-proton (pp) collisions at a center-of-mass energy of 13 TeV by the CMS experiment in 2017 and 2018, corresponding to an integrated luminosity of 101 fb^{-1}. A statistical combination is performed considering a model probed by an earlier search, conducted at the same center-of-mass energy with 36 fb^{-1} of data collected in 2016 [5].

The "mono-Higgs" signature arises from new interactions between DM and SM particles. Several models suggest enhanced couplings between BSM particles and scalar bosons [6–8]. Although the Higgs boson could theoretically be radiated from initial-state quarks, this process is highly suppressed because of small Yukawa couplings or loop processes [9–11]. This

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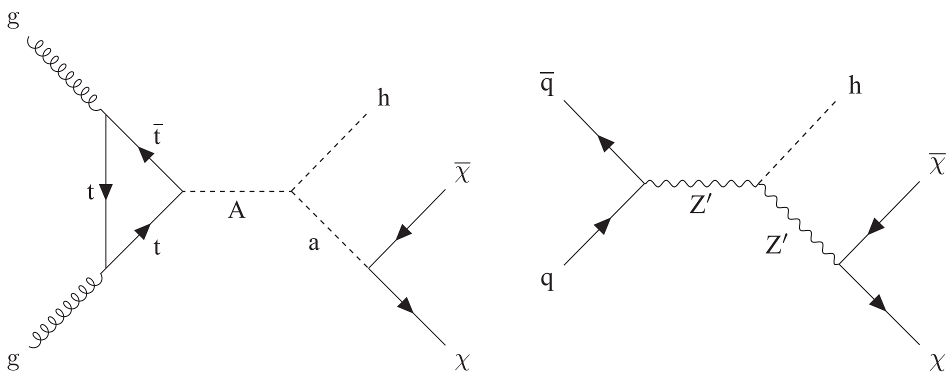

Figure 1. Representative Feynman diagrams for leading order DM-associated production of a Higgs boson in the 2HDM+a (left) and baryonic Z′ (right) models.

analysis considers two simplified benchmark models for DM+h production [12]. The 2HDM+a model [13, 14] is a canonical two Higgs doublet model with an additional pseudoscalar singlet interacting with DM particles. This model features five Higgs bosons: one SM-like Higgs boson (h), two charged Higgs bosons ($H^{\pm}$), one heavier neutral scalar (H), and one heavier neutral pseudoscalar (A), as well as an additional pseudoscalar (a). The Feynman diagram describing DM production in this model is shown in figure 1 (left). The baryonic Z′ model [9] predicts a new massive vector mediator Z′ that can emit a Higgs boson and then decay to a pair of Dirac fermionic DM particles, leading to the Feynman diagram shown in figure 1 (right).

According to ref. [12], a benchmark scenario is defined by fixing several model parameters based on both electroweak and flavor measurements and phenomenological considerations, such as the requirement that the Higgs potential is stable. Assuming the alignment of the 2HDM+a model and the decoupling limits, m_{h} is set to 125 GeV. From electroweak precision constraints, the masses of the heavier Higgs bosons ($H^{\pm}$, H, A) are set to be equal, leaving five free parameters of the model: the mass of the light pseudoscalar m_{a}, the mass of the heavy pseudoscalar m_{A}, the mass of the DM candidate, m_{χ}, $\sin\theta$, where θ is the mixing angle of the two CP-odd weak spin-0 eigenstates, and the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$. The variations of the $\sin\theta$ and $\tan\beta$ parameters change the signal strength and have a prominent impact on the shapes of the $p_{\mathrm{T}}^{\mathrm{miss}}$ distribution of the mono-Higgs production.

In the baryonic Z′ model [9], the baryonic gauge boson Z′ arises from a new $U(1)_{\mathrm{B}}$ baryon number symmetry. A baryonic Higgs boson ($\mathrm{h_B}$) is introduced to break this symmetry spontaneously, generating the Z′ boson mass via a coupling dependent on the $\mathrm{h_B}$ vacuum expectation value. The Z′ boson couplings to quarks and DM particles are proportional to the $U(1)_{\mathrm{B}}$ gauge couplings. There is a mixing between $\mathrm{h_B}$ and the 125 GeV Higgs boson (h), allowing the Z′ to radiate an h. The coupling strength between the Z′ boson and h is $g_{h\mathrm{Z}'\mathrm{Z}'}$ $= (m_{\mathrm{Z}'}^2 \sin\zeta)/v_B$, where the parameter $\sin\zeta$ governs the mixing angle between the $\mathrm{h_B}$ and h, and v_B is the vacuum expectation value of $\mathrm{h_B}$. In this model, stable baryonic states are the candidate DM particles. This paper considers a Z′ resonance with a mass between 10 and 2500 GeV, and DM particle masses between 1 and 800 GeV. As suggested in ref. [15], the mediator-DM coupling is fixed to 1, and the mediator-quark coupling to 0.25 to avoid the constraints from dijet searches at the LHC.

Although the branching ratio of the SM Higgs boson to two τ leptons is lower than that to $\mathrm{b\overline{b}}$, this analysis takes advantage of several distinct benefits of the h that decays to a τ pair. It benefits from small SM backgrounds and does not rely on $p_{\mathrm{T}}^{\mathrm{miss}}$ triggers. As a result, the ττ channel serves as a complementary approach to the bb channel, enabling the exploration of dark matter scenarios with lower $p_{\mathrm{T}}^{\mathrm{miss}}$ values.

SM processes can also give rise to a signature with $p_{\mathrm{T}}^{\mathrm{miss}}$ and two τ leptons consistent with the decay products of a Higgs boson. One such important SM process is the production of a Higgs boson in association with a Z boson that decays into neutrinos. Although this process has a relatively low cross section, it may produce final states indistinguishable from the signal. Other SM processes that can result in final states with $p_{\mathrm{T}}^{\mathrm{miss}}$ and two τ lepton decays include the production of a Z boson, a pair of vector bosons (WW, WZ, ZZ), a top quark-antiquark pair, or a Higgs boson in association with a W boson. Separating the signal from these processes is challenging because of their higher cross sections, finite detector resolution, acceptance limitations, and the inherent uncertainty introduced by the presence of two neutrinos, which can potentially mimic signal events.

The previous search in the same final state by the CMS experiment [5] was based on data collected at a center-of-mass energy of 13 TeV and corresponding to an integrated luminosity of 36 fb^{-1}. These results were interpreted in terms of the baryonic Z' model. A similar search was conducted by the ATLAS experiment at a center-of-mass energy of 13 TeV, using a data set corresponding to an integrated luminosity of 139 fb^{-1} [16]. The results of this search were interpreted in terms of a 2HDM+a model featuring two scalar Higgs doublets and a pseudoscalar singlet field. No significant excess over the SM prediction was observed in either study.

The analysis reported here benefits from a larger data set and employs a method based on control samples in data, known as the "misidentification factor (MF) method", described in refs. [17, 18]. This method collectively estimates background events with quark- or gluon-jets misidentified as hadronically decaying τ leptons (τ_{h}), instead of measuring this background separately for W+jets and multijet events arising from quantum chromodynamics (QCD).

The remainder of this paper is organized as follows. In section 2, the CMS detector and the reconstruction of the objects and event variables used in the analysis are introduced. Section 3 details the data set and the Monte Carlo (MC) simulated samples used in the analysis. Section 4 describes the event selection and analysis strategy for the study, while section 5 outlines the systematic uncertainties affecting the analysis. Finally, section 6 presents the results and their interpretation, and a summary is provided in section 7. The tabulated results are also provided in the HEPData record [19].

2 The CMS detector and event reconstruction

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel

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and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

Events of interest are selected using a two-tiered trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μs [20]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to a few kHz before data storage [21, 22]. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in refs. [23, 24].

The particle-flow (PF) algorithm [25] combines information from all the different parts of the CMS detector to identify and reconstruct individual particles. These particles, called PF candidates, can be charged or neutral hadrons, electrons, photons, or muons. The reconstructed track vertex with the largest value of summed physics-object p_{T}^2, where p_{T} is the transverse momentum of the objects, is taken to be the primary vertex (PV) of the pp interaction. Any other collision vertices in the event are associated with additional mostly soft inelastic pp collisions called pileup (PU). In the 2017–2018 data sets the average number of interactions per bunch crossing was 32.

Electron candidates are reconstructed by combining clusters of energy deposits in the ECAL with hits in the silicon tracker [26]. The momentum resolution for electrons with $p_{\mathrm{T}} \approx 45$ GeV from $\mathrm{Z} \to \mathrm{ee}$ decays ranges from 1.6 to 5%. Electron identification is performed using a multivariate discriminant derived from track quality, shower shape, and kinematic quantities. For this analysis, a medium working point with an identification efficiency of 90% is used, with a misidentification rate of ≈1% from jets in the relevant kinematic region [26]. Muons are measured using detection planes that employ three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers [27]. Muons in the event are reconstructed by performing a simultaneous track fit to hits in the tracker and in the muon chambers. The momentum resolution, for muons with p_{T} up to 100 GeV, is 1% in the barrel and 3% in the endcaps. The p_{T} resolution in the barrel is better than 7% for muons with p_{T} up to 1 TeV. For this study, muon identification requirements with an efficiency of approximately 99% are chosen, with a misidentification rate below 0.2% for pions [26].

The contribution of backgrounds with misidentified electrons or muons can further be minimized by isolating the corresponding lepton candidate from any hadronic activity. The isolation variable, defined by the following eq. (2.1), is used:

$$I_{\mathrm{rel}}^{\ell} = \frac{1}{p_{\mathrm{T}}^{\ell}} \left[\Sigma p_{\mathrm{T}}^{\mathrm{charged}} + \max\left(0, \Sigma E_{\mathrm{T}}^{\mathrm{neutral}} + \Sigma E_{\mathrm{T}}^{\gamma} - p_{\mathrm{T}}^{\mathrm{PU}}\right)\right], \tag{2.1}$$

where lepton ℓ refers to either an electron or muon, p_{T}^{ℓ} corresponds to the lepton p_{T}, $\Sigma p_{\mathrm{T}}^{\mathrm{charged}}$ corresponds to the p_{T} sum of all charged particles, and $\Sigma E_{\mathrm{T}}^{\mathrm{neutral}}$ and $\Sigma E_{\mathrm{T}}^{\gamma}$ correspond to the transverse energy E_{T} sum of neutral hadrons and photons, respectively. This isolation is predefined in a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ around the lepton direction at the PV, where $\Delta\eta$ and $\Delta\phi$ (measured in radians) correspond to the angular distances of the particle to the lepton in the η and ϕ directions, respectively. The cone sizes for electrons and

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muons are $\Delta R = 0.3$ and 0.4, respectively. The lepton itself is excluded from the isolation calculation. To mitigate the contamination from PU, only those charged particles whose tracks are associated with the PV are taken into account. For neutral hadrons and photons, it is hard to determine whether they originate from the PV or from PU. To account for this, an estimated contribution from PU ($p_{\mathrm{T}}^{\mathrm{PU}}$) is subtracted from the total measured energy of neutral hadrons and photons. For electrons, this is estimated from the mean energy flow per unit area, while for muons it is obtained from tracks not associated with the PV. The isolation criteria mentioned in section 4.1 have an efficiency for isolated electrons and muons from τ lepton decays well above 95%.

For each event, hadronic jets are reconstructed from the PF candidates using the infrared- and collinear-safe anti-k_{T} algorithm [28, 29] with a distance parameter R of 0.4. Jet momentum is determined as the vector sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5 to 10% of the true momentum over the entire p_{T} spectrum and detector acceptance [30]. In 2017, the ECAL endcaps were subject to an increased noise level affecting the reconstruction of jets. Jets with $p_{\mathrm{T}} < 50\,\mathrm{GeV}$ in the range of $2.65 < |\eta| < 3.14$ have been excluded from the analysis. Jets resulting from the hadronization of b quarks are used to separate signal from top quark-antiquark pair ($\mathrm{t\bar{t}}$) events. These are tagged by exploiting the neural net based DeepCSV algorithm as described in refs. [31, 32]. The medium working point for DeepCSV is chosen, which achieves approximately 66% efficiency with a 1% misidentification probability. Jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 4.7$ and b jets with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 2.5$ are used.

Jet energy corrections are derived from simulation to bring the measured response of jets to that of particle-level jets on average. In situ measurements of the momentum balance in dijet, γ+jet, Z+jet, and multijet events are used to account for any residual differences in the jet energy scale (JES) and jet energy resolution (JER) in data and simulation [30]. The JER amounts typically to 15–20% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV [30]. Additional selection criteria [33] are applied to each jet to remove jets potentially dominated by anomalous contributions from various subdetector components or reconstruction failures.

Hadronic τ lepton decays (τ_{h}) are reconstructed from jets using the hadrons-plus-strips algorithm [34], which combines one or three tracks with energy deposits in the calorimeters to identify the decay modes. Neutral pions are reconstructed by clustering the PF electrons and photons falling in η-ϕ regions, called the strips, with a dynamic size in η-ϕ, where the strip size varies as a function of the p_{T} of the electron or photon candidate. To distinguish genuine τ_{h} decays from jets originating from the hadronization of quarks or gluons, and from electrons, or muons, the DeepTau algorithm is used [35]. Information from all individual reconstructed particles near the τ_{h} axis is combined with properties of the τ_{h} candidate and the event. The input variables to the neural net include variables related to the τ_{h}, four-momentum, charge, lifetime, isolation, the compatibility of the τ_{h} track with the PV, observables associated with the η and ϕ distributions of the energy reconstructed in the strips, and other variables. The thresholds on the output discriminants [35], dependent on p_{T}, are chosen to define several working points, which provide good τ_{h} identification efficiencies. Table 1 shows the target τ_{h} identification efficiences for the different working points that are used in the analysis to discriminate against electrons (D_{e}), muons (D_{μ}), and jets (D_{jet}).

	Tight	Medium	VLoose	VVVLoose
D_{e}	80%	—	—	99.5%
D_{μ}	99.5%	—	99.95%	—
D_{jet}	—	70%	—	98%

Table 1. Target τ_{h} identification efficiencies for the different working points defined for the three different discriminants that are used in the analysis. These identification efficiencies are evaluated for genuine τ_{h} candidates in simulated $\mathrm{H} \to \tau\tau$ events with $p_{\mathrm{T}} \in [30, 70]$ GeV for τ_{h}.

The probability of a jet to be misidentified as a τ_{h} candidate by the DeepTau algorithm depends on the p_{T} and quark flavor of the jet. In simulated events from W boson production in association with jets, it has been estimated to be 0.43% for a genuine τ_{h} identification efficiency of 70%. The misidentification rate for electrons (muons) is 2.60 (0.03)% for a genuine τ_{h} identification efficiency of 80 (>99)%.

The negative vector sum of the transverse momenta ($\vec{p}_{\mathrm{T}}^{\text{miss}}$) is computed from all the PF candidates in an event, and its magnitude is denoted as $p_{\mathrm{T}}^{\text{miss}}$ [36]. The value of $\vec{p}_{\mathrm{T}}^{\text{miss}}$ is adjusted to account for corrections to the energy scale and resolution of the reconstructed jets in the event. Anomalous high-$p_{\mathrm{T}}^{\text{miss}}$ events can arise from various issues such as reconstruction failures, detector malfunctions, or non-collision backgrounds. These events are rejected by dedicated filters that are designed to eliminate more than 85–90% of the spurious high-$p_{\mathrm{T}}^{\text{miss}}$ events with a signal efficiency exceeding 99.9% [36]. The $p_{\mathrm{T}}^{\text{miss}}$ is used for the discrimination of W boson production in association with jets (W+jets) from signal by exploiting the transverse mass:

$$m_{\mathrm{T}}^{\ell} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\text{miss}} (1 - \cos \Delta\phi)}, \tag{2.2}$$

where ℓ stands for an electron or a muon, and $\Delta\phi$ is the azimuthal angular separation between p_{T}^{ℓ} and $p_{\mathrm{T}}^{\text{miss}}$.

3 Data and simulated samples

The analysis is performed with pp collision data at $\sqrt{s} = 13$ TeV collected with the CMS detector in 2017 and 2018. The data correspond to an integrated luminosity of 101 fb^{-1}. The analysis strategy and event selection were optimized using simulated samples of associated DM+h ($\tau\tau$) production via the two benchmark models discussed in section 1. The MadGraph5_aMC@NLO v2.6.0 [37] generator is used to generate both the 2HDM+a and baryonic Z′ signals at leading order (LO). The decay of the SM-like Higgs boson is simulated by PYTHIA 8.205 [38] using the CP2 tune [39].

The simulation is performed for mass values scanning the available phase space in the (m_{a},m_{A}) plane, for the 2HDM+a model (see table 2), and in the (m_{χ},$m_{\mathrm{Z}'}$) plane for the baryonic Z′ model (see table 3).

The largest backgrounds are $\mathrm{Z}/\gamma^{*} \to \ell\ell/\tau\tau$, W+jets, $\mathrm{t\bar{t}}$, single top quark, and multiboson processes. The MadGraph5_aMC@NLO v2.4.2 generator is used for the $\mathrm{Z}/\gamma^{*} \to \ell\ell/\tau\tau$ and W+jets processes, which are generated at LO in perturbative QCD with the MLM

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m_A [GeV]	m_a [GeV]									
	$\tan\beta = 1$, $\sin\theta = 0.35$, $m_\chi = 10\,\text{GeV}$									
225	100									
250		125								
300	100		150							
400	100		150	200	250					
500			150	200	250	300		375		
600	100		150	200	250	300	350		400	500
700	100			200	250	300	350		400	
800	100		150	200	250	300	350			500
900	100		150	200	250	300	350		400	500
1000	100		150		250		350			
1200			150		250		350			

Table 2. Mass values scanning the available phase space in the (m_a,m_A) plane, used in the simulation for the 2HDM+a model. The phase space is limited by $m_A - m_a < 125\,\text{GeV}$, where 125 GeV is the Higgs mass.

$m_{Z'}$ [GeV]	m_χ [GeV]											
200	1											
300	1	50										
350			100									
500	1	50	100									
650		50	100	150								
700						225						
750						225						
800		50		150	200		250	300	325			
900				150								
1000	1	50	100									
1100		50										
1500	1	50	100		200					400	600	
2000	1		100		200					400		800
2500	1											

Table 3. Mass values scanning the available phase space in the (m_χ,$m_{Z'}$) plane, used in the simulation for the baryonic Z′ model. The phase space is limited by $m_{Z'} - 2m_\chi < 125\,\text{GeV}$, where 125 GeV is the Higgs mass, and by $m_\chi < m_{Z'}/2$.

jet matching and merging scheme [40]. The $Z/\gamma^* \to \ell\ell/\tau\tau$ background is normalized to the cross section calculated at next-to-next-to-LO (NNLO) precision [41] and is corrected for differences in the dilepton invarient mass ($m^{\ell\ell/\tau\tau}$) and transverse momentum ($p_T^{\ell\ell/\tau\tau}$) distributions using dimuon events in data [42].

The reducible SM backgrounds with genuine Higgs bosons are produced via different processes: gluon-gluon fusion (ggh), vector boson fusion (VBF), in association with a vector boson (Vh), or in association with a pair of top quarks ($t\bar{t}h$). These Higgs boson samples are all generated using POWHEG 2.0 [43–46] at next-to-LO (NLO) in perturbative QCD. The $t\bar{t}$ and single top quark processes are generated at NLO with the POWHEG 2.0 generator. The FxFx [47] merging scheme is used to generate diboson backgrounds with the MadGraph5_aMC@NLO generator at NLO.

All simulated samples mentioned above use the NNPDF 3.1 NNLO parton distribution function (PDF) sets [48, 49] with the perturbative order matching that used in the matrix element calculations. For parton showering and hadronization, as well as for τ lepton decays, the samples are interfaced with PYTHIA using the CP5 tune [39]. The MC samples are processed through a full simulation of the CMS detector based on Geant4 [50] and are reconstructed with the same algorithms that are used for data. Minimum-bias collision events generated with PYTHIA are added to the simulated samples to reproduce the PU effects in the data.

4 Analysis strategy

The search is conducted by categorizing events on the basis of the decay modes of the τ leptons. This analysis focuses on the three τ lepton pair final states with the highest branching fractions: $e\tau_h$, $\mu\tau_h$, and $\tau_h\tau_h$. In the $e\tau_h$ and $\mu\tau_h$ channels, one τ lepton decays leptonically to an electron or a muon along with two neutrinos, while the other τ lepton decays hadronically (τ_h) with one neutrino. In the $\tau_h\tau_h$ channel, both τ leptons decay hadronically, each with one neutrino. The $e\mu$, ee, and $\mu\mu$ final states are excluded because of the low branching fraction of $\tau\tau$ pairs to purely leptonic final states. Additionally, the ee and $\mu\mu$ final states are heavily dominated by the Drell-Yan production of lepton pairs. The search is performed separately for the 2017 and 2018 data sets and then combined statistically for the two data-taking years, as well as with the published 2016 results [5].

4.1 Event selection

To select events in the $e\tau_h$ and $\mu\tau_h$ channels, triggers based on the presence of a single electron or muon are employed. Additionally, in the $e\tau_h$ channel, a trigger relying on the presence of an electron and a τ_h candidate is also used. For the $\tau_h\tau_h$ channel, the triggers require the presence of two isolated τ_h objects. Each offline reconstructed τ_h candidate must be matched to a τ_h candidate at the trigger level with a ΔR separation of less than 0.5. The efficiency of the online selection generally exceeds 90% after the offline selection described below, and it does not exhibit strong kinematic dependencies for the leptons selected for the offline analysis, as verified with independent triggers. Events in each channel must satisfy the respective offline selection criteria for p_T, η, and $I_{rel}^{e(\mu)}$, as described in table 4. These criteria are chosen to be efficient with respect to the online selection.

Final state	Observable	First lepton	Second lepton
$e\tau_h$	$p_T >$	25 GeV	30 GeV
	$\|\eta\| <$	2.1	2.3
	$I^e_{rel} <$	0.15	—
$\mu\tau_h$	$p_T >$	29 GeV	30 GeV
	$\|\eta\| <$	2.4	2.3
	$I^\mu_{rel} <$	0.15	—
$\tau_h\tau_h$	$p_T >$	55 GeV	45 GeV
	$\|\eta\| <$	2.1	2.1

Table 4. Offline selection requirements applied to e, μ, and τ_h candidates used for the selection of τ pairs. The expressions "first lepton" and "second lepton" refer to the lepton order of the final state in the first column.

For the $e\tau_h$ channel, events are selected based on the presence of at least one electron and one τ_h candidate. The electron must satisfy a multivariate identification criterion with 90% efficiency [26]. It is also required to be isolated from any hadronic activity in the detector, with a relative isolation requirement of $I^e_{rel} < 0.15$. Additionally, the electron and τ_h candidate must have opposite charge and be separated by $\Delta R > 0.5$ in the η-ϕ plane. The τ_h candidate must pass the "Medium" DeepTau discriminant against jets. To reduce the contribution from background processes where an electron or muon is misidentified as a τ_h, the selected τ_h candidate must satisfy the anti-lepton discriminators, "Tight" against electrons, and "VLoose" against muons, as detailed in table 1.

Similarly, for the $\mu\tau_h$ channel, events are selected based on the presence of at least one muon and one τ_h candidate. The muon must satisfy a PF-based identification criterion with ≈95% efficiency [27]. It is also required to be isolated from any hadronic activity in the detector, with a relative isolation requirement of $I^\mu_{rel} < 0.15$. Additionally, the muon and τ_h candidate must have opposite charge and be separated by $\Delta R > 0.5$ in the η-ϕ plane. The τ_h candidate must pass the "Medium" DeepTau discriminant against jets, the "VVVLoose" discriminant against electrons, and the "Tight" discriminant against muons, as detailed in table 1.

Two types of vetoes are implemented in the $e\tau_h$ and $\mu\tau_h$ channels to reject backgrounds. First, events containing b-tagged jets with $p_T > 25$ GeV and $|\eta| < 2.4$ are vetoed to suppress contributions from $t\bar{t}$ and single top quark processes. Second, to mitigate contributions from backgrounds with multiple leptons, events containing additional electrons or muons, each with $p_T > 10$ GeV and $|\eta| < 2.4$, aside from the τ candidates, are excluded from further analysis. The additional electron or muon must satisfy similar identification criteria as the leading lepton but without the isolation requirement.

In the $\tau_h\tau_h$ channel, events are selected based on the presence of two oppositely charged τ_h leptons. The two τ_h candidates must be separated in the η-ϕ plane by $\Delta R > 0.5$. Both the τ_h candidates must pass the "Medium" DeepTau discriminant against jets, the "VVVLoose" discriminant against electrons, and the "VLoose" discriminant against muons, as detailed in table 1.

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In addition, for all three τ pair categories, $p_{\mathrm{T}}^{\mathrm{miss}}$ is required to be greater than 105 GeV and the visible p_{T} of the $\tau\tau$ system must exceed 65 GeV. These stringent criteria reduce the need for isolation in the $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$ channel. Additionally, the visible mass of the $\tau\tau$ system must be less than 125 GeV to ensure that the $\tau\tau$ system is compatible with an SM Higgs boson. To minimize diboson and W+jets contributions, the two τ candidates must pass a loose criterion of $\Delta R_{\tau\tau} < 2.0$. Furthermore, a selection on the total transverse mass ($M_{\mathrm{T}}^{\mathrm{tot}}$) greater than 100 GeV is required. The $M_{\mathrm{T}}^{\mathrm{tot}}$ distribution is used to extract the signal for this analysis and is defined as:

$$M_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{(E_{\mathrm{T}}^{\tau_1} + E_{\mathrm{T}}^{\tau_2} + p_{\mathrm{T}}^{\mathrm{miss}})^2 - (p_x^{\tau_1} + p_x^{\tau_2} + p_x^{\mathrm{miss}})^2 - (p_y^{\tau_1} + p_y^{\tau_2} + p_y^{\mathrm{miss}})^2}, \tag{4.1}$$

where p_x^{miss} and p_y^{miss} are the magnitudes of the x and y components of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$. Here τ_1 and τ_2 are the leading and the subleading electrons, muons, or τ_{h} candidates in all three channels. This selection reduces the background contributions from the Drell-Yan backgrounds in the leptonic channels and is chosen to maximize the expected significance of the analysis.

During the 2017 data taking, a gradual shift in the timing of the inputs of the ECAL L1 trigger in the region at $|\eta| > 2.0$ caused a specific trigger inefficiency. For events containing in this region an electron or a photon with $p_{\mathrm{T}} \geq 50$ GeV, or a jet with $p_{\mathrm{T}} \geq 100$ GeV, the efficiency loss is up to $\approx 10-20\%$, depending on p_{T}, η, and time [20]. Correction factors are computed from data and applied to the acceptance evaluated from simulation for the 2017 samples. Finally, a section of the HCAL was not functioning during a part of the 2018 data-taking period corresponding to 65% of the total integrated luminosity recorded in that year, leading to irrecoverable mismeasurements in a localized region of the detector ($-1.57 < \phi < -0.87, -3.0 < \eta < -1.3$). To avoid contamination from such mismeasurements, events where any jet with $p_{\mathrm{T}} > 30$ GeV is found in the corresponding η-ϕ region are rejected in the analysis of the corresponding partial 2018 data set.

On top of JES corrections to $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, this analysis adopts an additional correction similar to that in ref. [42]. The differences between data and simulation are applied as corrections to the direction and magnitude of the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ in simulated events. Simulated $\mathrm{Z} \to \mu\mu$ events are used to estimate the hadronic recoil, which is then compared with selected $\mathrm{Z} \to \mu\mu$ events in data. This correction to $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is applied to Z+jets events. More details on this method can be found in ref. [36]. Additionally, for simulated $\mathrm{t\bar{t}}$ events, a top quark p_{T} reweighing is applied to match the p_{T} distribution observed in data [51].

4.2 Signal extraction and background estimation

Backgrounds are estimated using a combination of simulated samples and control samples in data. The major backgrounds arising from jets misidentified as τ_{h} candidates, including events from W+jets, QCD multijet, and $\mathrm{t\bar{t}}$ production, are estimated using data, with a so-called "misidentification factor method". The other backgrounds, from Z+jets, SM Higgs boson, single top quark, diboson production processes, and the background from $\mathrm{t\bar{t}}$ production with two real τ leptons, are estimated from simulation. The measurements of the cross sections for Drell-Yan [18] and single top quark [52] processes at the LHC are consistent with the NNLO theoretical predictions, within the quoted uncertainties, supporting the use of theory-based normalizations for these backgrounds.

The background with jets misidentified as τ_h candidates, called the "mis-ID background", is obtained with a method similar to that in ref. [53]. The method is based on measuring two quantities: the number of events where jets pass the nominal τ_h identification (ID) criteria (called isolated), corresponding to the signal region (SR) selection of the corresponding analysis, and the number of events where jets satisfy a set of loose ID criteria, but fail the nominal τ_h ID criteria (referred to as "antiisolated" in the following).

The MF is defined as the ratio of the two numbers:

$$\mathrm{MF} = \frac{\text{number of events passing preselection and Medium } D_{\text{jet}} \text{ ID discriminant}}{\text{number of events passing preselection and failing the Medium } D_{\text{jet}} \text{ ID discriminant}} \tag{4.2}$$

and is applied as a weight to events that pass the corresponding SR selection except that the events are required to select τ_h candidates satisfying the loose preselection criteria, but failing the nominal τ_h ID criteria (application region). The MF is estimated as a function of the jet multiplicity (0 or ≥ 1), separately for the QCD multijet, W+jets, and $t\bar{t}$ backgrounds. A control region (CR) enriched in QCD multijet events is obtained by applying the same selection as used in the analysis, except that the two τ leptons are required to be of the same sign (SS) instead of the opposite sign (OS). A CR enriched in W+jets events is obtained by applying the same selection as used in the analysis, except that the Higgs boson p_T, which is the visible p_T of the τ lepton pair, is required to be less than 65 GeV and m_T, which is the transverse mass of the lepton and the p_T^{miss}, is required to be greater than 70 GeV. Finally, a CR enriched in $t\bar{t}$ events is obtained by applying the same selection as used in the analysis, except that the number of b-tagged jets is required to be at least 1.

The following steps are performed successively to estimate the mis-ID background:

1. Measure the MFs as a function of the $p_T^{\tau_h}$: the MFs are derived as the ratio of isolated to antiisolated τ_h candidates in QCD, W+jets, and $t\bar{t}$ events in dedicated CRs, and are fitted with a linear function.

2. Correct the MFs as a function of the p_T of the lepton that is not misidentified: the correction is derived by comparing the distributions of isolated events in the CR with antiisolated events in the CR, reweighted with the raw MFs derived in the previous step.

3. Correct the MFs for differences in selection between the CRs and the SR: the correction in the QCD CR (OS/SS correction), and the differences in the selection of the Higgs boson p_T and the m_T in the W+jets CR. The correction for the inversion of the Higgs boson p_T and m_T selections in the W+jets CR is determined through simulations by comparing the isolated events in the CR to the weighted antiisolated events as a function of m_T. The correction for the sign inversion in the QCD CR is computed using data. It is determined as a function of visible mass of the $\tau\tau$ system in a CR with antiisolated lepton i.e $0.1 < I_{\text{rel}}^{e} < 0.2$ ($0.15 < I_{\text{rel}}^{\mu} < 0.25$) in the $e\tau_h$ ($\mu\tau_h$) final state. The MF is computed by using step 1 and step 2 and is applied as a weight to OS events with an antiisolated tau and antiisolated lepton. These weighted events are then compared with OS events with anti-isolated lepton and an isolated tau to obtain the correction.

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Expected Backgrounds	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
$Z \to \tau_h\tau_h$	339 ± 49	557 ± 73	297 ± 38
$t\bar{t}$	542 ± 48	744 ± 61	99 ± 10
Single Top	94.9 ± 8.6	122 ± 10	11.8 ± 1.2
Diboson	133 ± 11	279 ± 27	34.5 ± 3.0
Other MC	64.4 ± 6.5	84.4 ± 7.0	50.7 ± 4.8
Jets $\to \tau_h$	1400 ± 68	2508 ± 95	79.1 ± 5.9
Total Background	2573 ± 98	4294 ± 138	572 ± 40
Data	2582	4311	581

Table 5. The post-fit estimated background yields and the observed number of events for the M_T^{tot} distribution in the SR, combined for the 2017 and 2018 data. The "Other MC" background contribution includes events from ggh, VBF, Wh, Zh, $Z \to$ Others, and electroweak vector boson production. The uncertainties in the total expected yields include both statistical and systematic contributions.

4. Determine the relative fraction of QCD, W+jets, and $t\bar{t}$ events: the $t\bar{t}$ and W+jets yields are estimated using simulations, whereas the QCD yield is estimated by subtracting all the backgrounds from data in the antiisolated region.

5. Apply the MFs weighted by the corresponding fractions, to obtain the mis-ID background from the simulated events in the SR.

The signal is extracted with a binned maximum likelihood fit to the M_T^{tot} distributions (eq. (4.1)) in the different channels for the SR.

Figure 2 shows the comparison of data and expected backgrounds for the M_T^{tot} distributions after the simultaneous likelihood fit to data in the SRs. Table 5 shows the post-fit yields extracted from the M_T^{tot} distribution for the expected number of background events and the number of events observed in 2017 and 2018 data combined. The observed number of events is in good agreement with the estimated number of events by the SM backgrounds.

5 Systematic uncertainties

All systematic uncertainties affecting the analysis are summarized along in table 6, with their correlations between data sets from different years and different final states. These uncertainties are considered as nuisance parameters within the likelihood function. The selection efficiency correction factors are applied to the signal and all the background processes estimated through simulations, and uncertainties are included that account for differences between simulation and observation in the reconstruction and identification efficiencies for various particle candidates.

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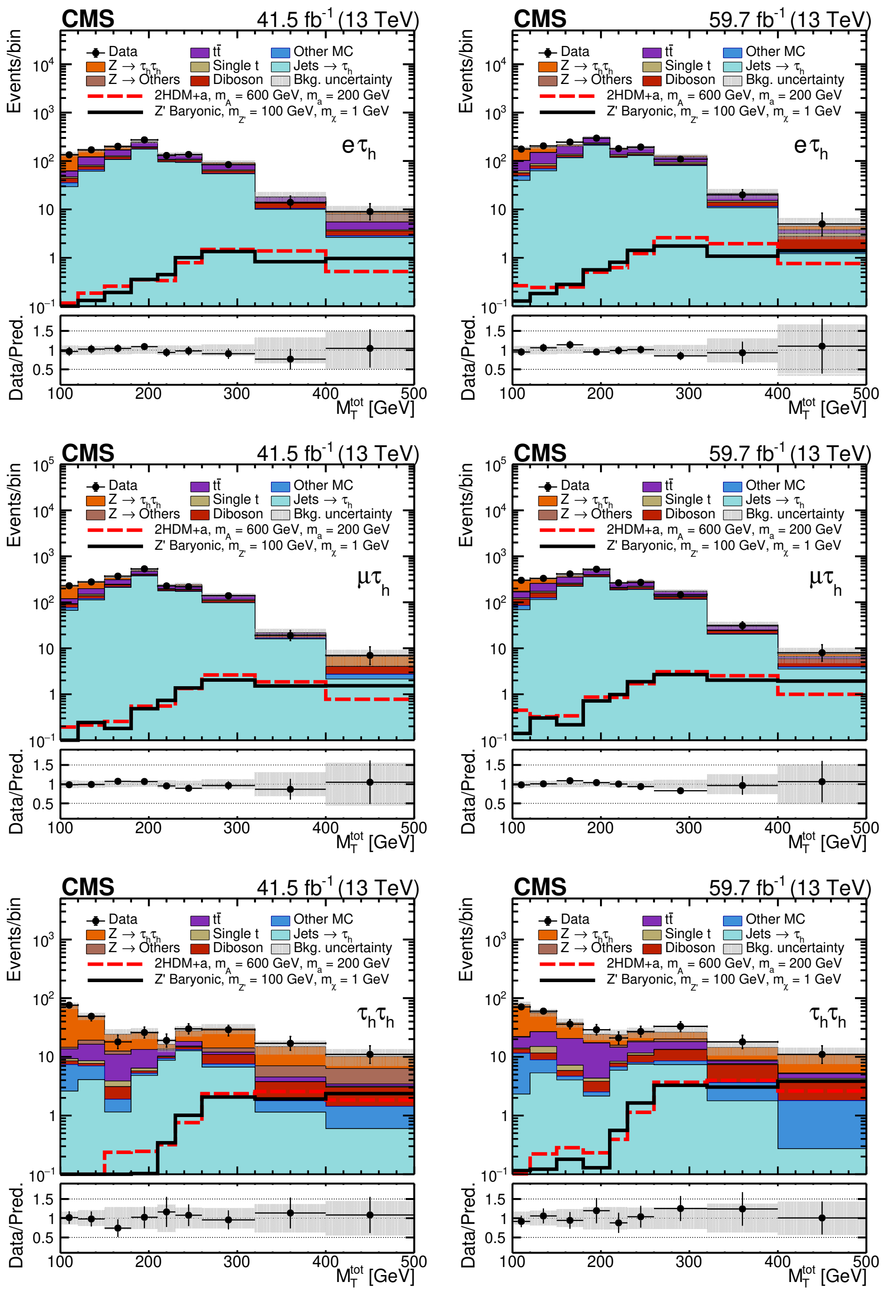

Figure 2. Distributions of the total transverse mass M_T^{tot} in the SRs, for observed data and SM prediction in the $e\tau_h$ (upper), $\mu\tau_h$ (center), and $\tau_h\tau_h$ (lower) final states in 2017 (left) and 2018 (right) after the simultaneous maximum likelihood fit. Representative signal distributions are shown for the 2HDM+a (dashed red curve) and baryonic Z′ (solid black curve) models. The data points are shown with their statistical uncertainties, and the last bin includes overflow. The "Other MC" background contribution includes events from ggh, VBF, Wh, Zh, and electroweak vector boson production. The uncertainty band accounts for all systematic and statistical sources of uncertainty, after the fit to the data.

Uncertainty	Magnitude	Correlation years	Correlation final states
τ_h identification	p_T-dependent	0%	100 (0)% for $\ell\tau_h$ ($\tau_h\tau_h$)
τ_h ID, for high $p_T^{\tau_h}$	Event-dependent	100%	100%
τ_h energy scale	0.7–1.2%	0%	100%
Electron misidentified as τ_h	Event-dependent	0%	0%
Muon misidentified as τ_h	Event-dependent	0%	0%
Electron/muon identification	2%	0%	0%
Energy scale for lepton mis-ID as τ_h	1%	0%	0%
Trigger	Event-dependent	0%	0%
Electron energy scale	Event-dependent	100%	100%
Muon energy scale	0.4–2.7%	100%	100%
b jet veto	Event-dependent	partial	100%
Integrated luminosity	2–3%	partial	100%
$t\bar{t}$ cross section	6%	100%	100%
Diboson cross section	5%	100%	100%
Single top quark cross section	5%	100%	100%
Drell-Yan cross section	4%	100%	100%
L1 mistiming	Event-dependent	0%	100%
Z boson p_T reweighting	10%	100%	100%
Top quark p_T reweighting	Event-dependent	100%	100%
JES	Event-dependent	100%	100%
JER	Event-dependent	100%	100%
$\vec{p}_T^{\,miss}$ unclustered ES	Event-dependent	0%	100%
$\vec{p}_T^{\,miss}$ recoil corrections	Event-dependent	0%	100%
MF in $\ell\tau_h$	Event-dependent	partial	0%
MF in $\tau_h\tau_h$	Event-dependent	partial	0%
MF in $\tau_h\tau_h$, for $p_T^{\tau_h} > 100\,\text{GeV}$	Event-dependent	0%	0%

Table 6. Systematic uncertainties with their source, magnitude and correlations between data samples from either different data-taking years or different final states.

The uncertainty in the τ_h identification efficiency is considered as a $p_T^{\tau_h}$- and decay-mode-dependent uncertainty ranging from 3 to 5% [35]. An additional shape-based uncertainty on the M_T^{tot} distribution in the range 10–15% is added for τ_h candidates with $p_T > 100\,\text{GeV}$. The uncertainty in the τ_h trigger efficiency is also $p_T^{\tau_h}$-dependent and ranges from 4 to 9%. Since both the τ_h identification and τ_h trigger uncertainties are statistically dominated, they are considered as uncorrelated across data-taking years.

An uncertainty covers the misidentification of electrons or muons as τ_h candidates. It is dependent on $p_T^{\tau_h}$, η, and the decay mode. It is also considered as uncorrelated between the samples of different data-taking years. The uncertainty in the τ_h energy scale is in the range 0.7–1.2%, depending on $p_T^{\tau_h}$ and on the τ_h decay mode. It is treated as uncorrelated between data-taking years and decay modes. An additional uncertainty of 1% is also considered for the energy scale of the misidentified leptons and it is considered uncorrelated across the data-taking years.

The uncertainty in the electron and muon reconstruction, efficiency, and identification is 2% for all years, uncorrelated across data-taking years [26, 27, 54]. The electron energy scale uncertainties are also derived event-by-event and are treated as shape uncertainties. Since they are systematically dominated [26], these uncertainties are treated as correlated across data-taking years. The uncertainty related to the muon energy scale is between 0.4 and 2.7%, and correlated between data-taking years. A shape-based uncertainty depending on p_{T} and η for the electron and muon triggers is considered.

For the background processes, cross section uncertainties of 5% for diboson and single top quark [52, 55–57], 4% for Drell-Yan [18, 41], and 6% for $\mathrm{t\bar{t}}$ backgrounds are also considered [55, 58]. An additional uncertainty of 1–2% to account for the L1 trigger ECAL timing shift is also considered. The uncertainties related to the integrated luminosities for the data-taking period 2017–2018 amounts to 2.3–2.5%, while overall uncertainty for total Run-2 period is 1.6% [59, 60]. In simulated Z+jets events, a shape uncertainty of 10% of the Z boson p_{T} reweighting correction, to account for higher-order effects, is used. A shape-based uncertainty is applied to the $\mathrm{t\bar{t}}$ process to correct the top quark p_{T} distribution. For the Drell-Yan process, where $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ recoil corrections are applied, an uncertainty in the calibration and resolution of the hadronic recoil are applied [36]. For all other background processes estimated from simulation, an uncertainty in $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ related to unclustered energy is taken into account. The $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ uncertainties are considered as uncorrelated across data-taking years. Uncertainties in the JES are included on an event-by-event basis and considered as correlated across data-taking years.

For the background with jets misidentified as τ_{h} candidates, different sources of uncertainty are considered. The MFs are parameterized linearly as function of $p_{\mathrm{T}}^{\tau_{\mathrm{h}}}$. Two uncertainties per fit function are considered. They are obtained by uncorrelating the fit uncertainties in the slope and intercept of the fit functions obtained in the three CRs, i.e, the W+jets, QCD multijet, and $\mathrm{t\bar{t}}$ CRs. A shape-based uncertainty for the lepton p_{T} correction for all three CRs is considered. An additional shape-based uncertainty to cover the OS/SS correction in the QCD CR is applied. A shape-based uncertainty is considered for τ_{h} candidates with $p_{\mathrm{T}} > 100\,\mathrm{GeV}$, following ref. [61].

6 Results

The results are extracted from a maximum likelihood fit, using the CMS statistical analysis tool COMBINE [62]. No significant excess of data above the SM background expectation is observed. Interpretations in the 2HDM+a and baryonic Z′ models are provided.

The signal upper limits are determined with the signal strength modifier $\mu = \sigma/\sigma_{\mathrm{theory}}$, where σ_{theory} is the predicted production cross section of the particular model considered, calculated using the parameter choices described in section 1, and σ corresponds to the upper limit on the observed cross section.

Upper limits are obtained using the data set collected in 2017–2018. They are calculated at 95% confidence level (CL) using the CLs criterion [63, 64] computed with an asymptotic approximation [65] by using the profile likelihood ratio modified for upper limits.

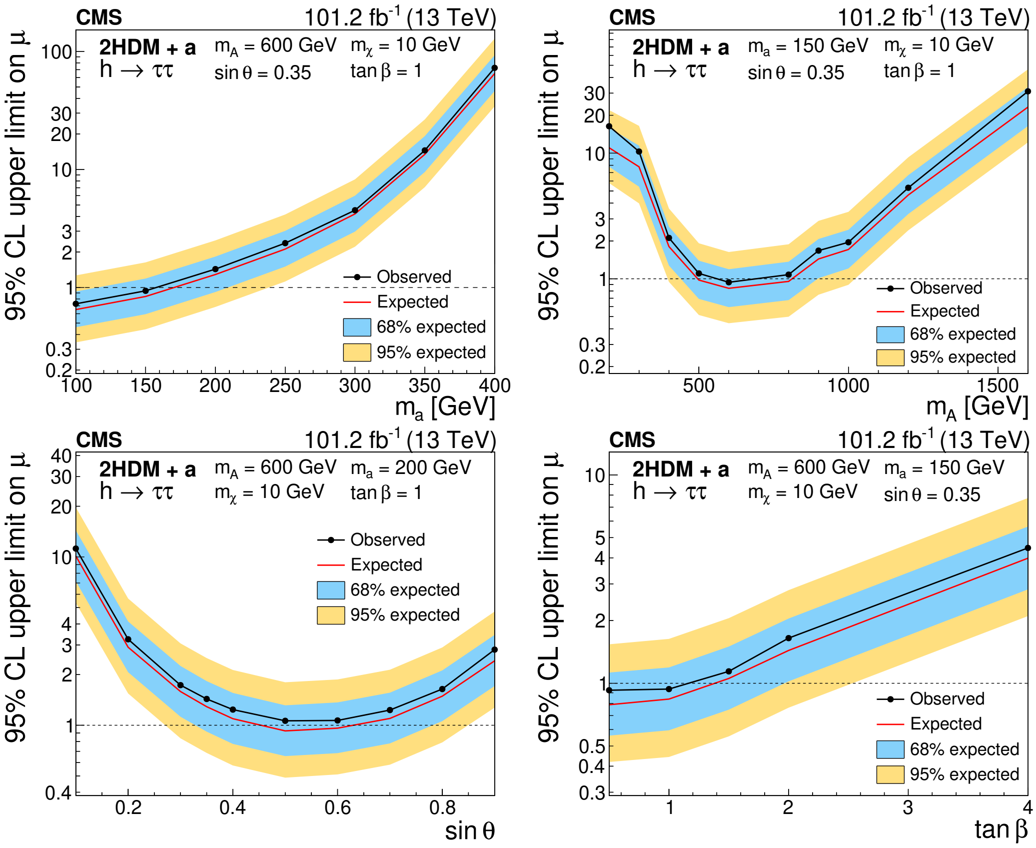

Figure 3. The 95% CL upper limits on μ for the 2HDM+a model as a function of m_{a} (upper let), m_{A} (upper right), $\sin\theta$ (lower left) and $\tan\beta$ (lower right). The values assumed for the other parameters are shown on each figure. The interpolation between the points is linear.

For the 2HDM+a model, the one-dimensional upper limits on μ as a function of the lighter pseudoscalar mass m_{a} are shown in figure 3 (upper left), using $\sin\theta = 0.35$, $m_{\mathrm{A}} = 600\,\mathrm{GeV}$, $\tan\beta = 1$, and $m_\chi = 10\,\mathrm{GeV}$. Similar limits as functions of m_{A} are shown in figure 3 (upper right), using $\sin\theta = 0.35$, $m_{\mathrm{a}} = 150\,\mathrm{GeV}$, $\tan\beta = 1$, and $m_\chi = 10\,\mathrm{GeV}$. Upper limits on μ as a function of $\sin\theta$ ($\tan\beta$) are shown in figure 3 lower left (lower right), using $m_{\mathrm{a}} = 200\,\mathrm{GeV}$, $m_{\mathrm{A}} = 600\,\mathrm{GeV}$, $\tan\beta = 1$, and $m_\chi = 10\,\mathrm{GeV}$ ($m_{\mathrm{a}} = 150\,\mathrm{GeV}$, $m_{\mathrm{A}} = 600\,\mathrm{GeV}$, $\sin\theta = 0.35$, and $m_\chi = 10\,\mathrm{GeV}$).

Two-dimensional limits in the (m_{A},m_{a}) plane, using $\sin\theta = 0.35$, $\tan\beta = 1$, and $m_\chi = 10\,\mathrm{GeV}$ are shown in figure 4. Masses of m_{A} between 400 and 700 GeV are excluded for small values of m_{a} ($m_{\mathrm{a}} \approx 100\,\mathrm{GeV}$).

The one-dimensional upper limits on μ for the baryonic Z$'$ model, as a function of $m_{\mathrm{Z}'}$ are shown in figure 5 (left), using 138 fb^{-1} of data collected in 2016–2018. The two-dimensional limits on μ in the ($m_{\mathrm{Z}'}$,m_χ) plane are shown in figure 5 (right). In the previous result based on 2016 data, the observed exclusion region for the mediator mass reached 450 GeV for a DM mass of 1 GeV. After combination with the search based on 2017 and 2018 data presented in this paper, the observed (expected) exclusion region for $m_{\mathrm{Z}'}$ extends to around 1050 (1150) GeV for the same DM mass.

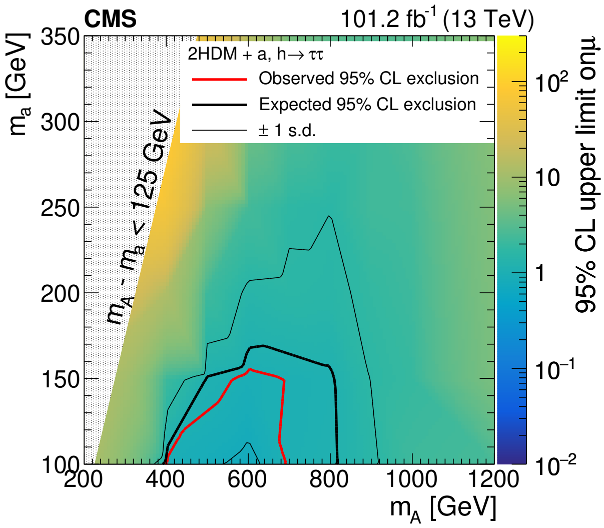

Figure 4. The 95% CL upper limits on μ in the $(m_{\mathrm{A}},m_{\mathrm{a}})$ plane for the 2HDM+a model. The regions inside the red and black curves correspond to the observed and expected exclusions at 95% CL, respectively.

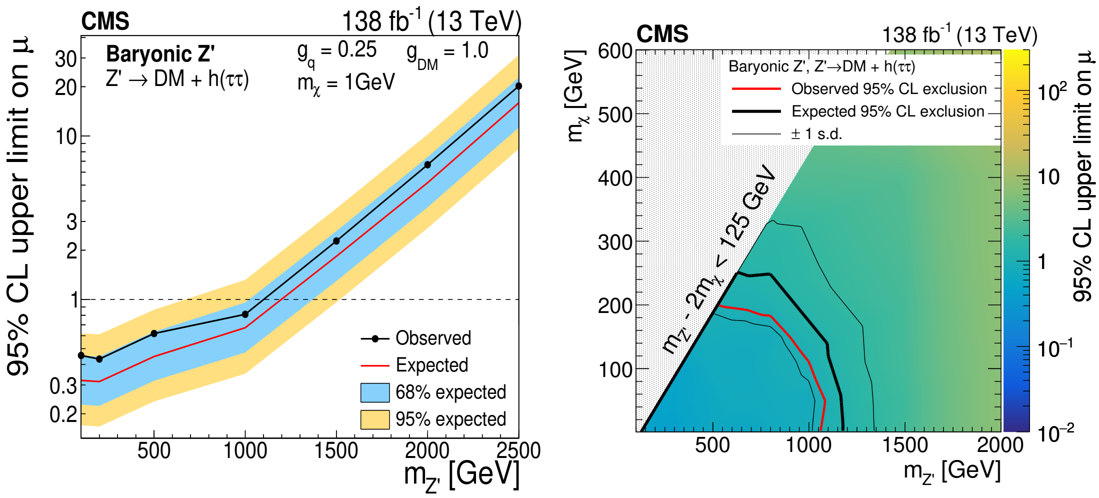

Figure 5. The 95% CL upper limits on μ for the baryonic Z' model. Left: observed and expected 95% CL upper limits on μ as a function of $m_{\mathrm{Z}'}$, using $m_\chi = 1\,\mathrm{GeV}$. Right: 95% CL upper limits on μ in the $(m_{\mathrm{Z}'},m_\chi)$ plane. The regions inside the red and black curve correspond to the observed and expected exclusions at 95% CL, respectively.

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7 Summary

A search for dark matter produced in association with a Higgs boson decaying to a pair of τ leptons has been performed using a data set of proton-proton collisions at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 101 fb^{-1}. The results are interpreted within the framework of two benchmark simplified models: the 2HDM+a model, where a heavy pseudoscalar couples to a Higgs boson and a lighter pseudoscalar that decays to dark matter particles, and the baryonic Z' model, where a high mass resonance (Z') decays into a pair of dark matter particles and a standard model Higgs boson. Upper limits at the 95% confidence level are set on the product of the production cross section and branching fraction for both models. In the 2HDM+a model, heavy pseudoscalar masses between 400 and 700 GeV are excluded for a light pseudoscalar mass around 100 GeV. For the baryonic Z' model, the results are combined with those of an earlier search using an independent data set collected at the same center-of-mass energy, corresponding to an integrated luminosity of 36 fb^{-1}. Z' masses up to 1050 GeV are excluded for a dark matter particle mass of 1 GeV, based on a data sample corresponding to a total integrated luminosity of 138 fb^{-1}.

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Data Availability Statement. Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use, and open access policy.

Code Availability Statement. The CMS core software is publicly available on GitHub.

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